

RF Diode Peak Detector Calibration For the CKM SCRF Q-Measurement System

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Abstract: A diode peak detector calibration procedure using a natural solution is presented. The calibration procedure is applied to the CKM (Charged Kaons at the Main Injector) Superconducting Radio Frequency (SCRF) cavity quality factor measurement system detectors.

Introduction

Any accurate RF envelope measurement using a diode peak detector must calibrate out the detector response. Although a simplified diode detector circuit has a complex solution for the output voltage in terms of the input voltage, the inverse solution is quite simple and is more natural than a polynomial fit. The solution is presented along with a calibration procedure and its application to the CKM SCRF cavity quality factor (Q) measurement system detectors.

The Diode Detector Circuit Solution

Figure 1 shows a simplified diode peak-detector circuit model. Assuming that the diode responds only to the envelope of the source voltage and that the source envelope is constant, a simplified analysis of the circuit can be performed.

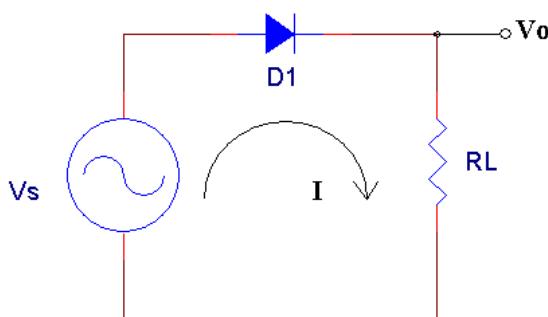


Figure 1: Simplified Diode Peak Detector Model

The voltage source, V_s , is assumed to be a DC source. The diode current-voltage relationship is approximated as¹

$$i_D = I_s \left(e^{\frac{v_D}{c_1}} - 1 \right) \quad (1)$$

where v_D is the voltage across the diode, c_1 is a physical constant, and I_s is the saturation current of the diode. Solving Eq.1 for v_D results in

$$v_D = c_1 \ln \left(\frac{i_D}{I_s} + 1 \right). \quad (2)$$

The current in the circuit, I , is expressed as,

$$I = \frac{V_o}{R_L} = i_D. \quad (3)$$

Using the above equations, the source voltage can be expressed as,

$$V_s = V_o + v_D \quad (4)$$

$$V_s = V_o + c_1 \ln \left(\frac{V_o}{R_L I_s} + 1 \right) \quad (5)$$

¹ See A.S.Sedra & K.C.Smith, *Microelectronic Circuits*, 3rd Edition, Saunders College Publishing, NY, 1991, Chapter 3.

Equation 5 suggests that the source voltage, V_s , can be calculated from the measured output voltage, V_o , using an equation of the form

$$V_s = c_0 V_o + c_1 \ln(c_2 V_o + 1) \quad (6)$$

where c_0 , c_1 , and c_2 are coefficients.

Given a set of measurements of V_s versus V_o for an actual detector, the coefficients of Eq.6 can be determined using a generalized regression method.

Calibration Procedure

The diode detector calibration procedure consists of applying a known source voltage and measuring the output voltage. The experimental setup used for the CKM SCRF Q-measurement system detectors is shown in Fig.2.

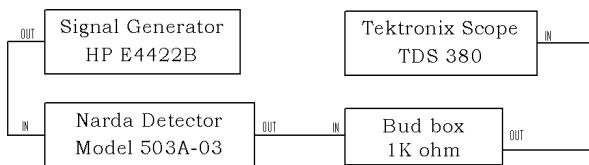


Figure 2: Detector Output Response Calibration Measurement Setup

The detector circuit is made up of both the Narda diode and the $1\text{k}\Omega$ load. The Tektronix Scope is the actual scope used in the Q-measurement system. Thus the calibration also includes the detector output measurement device. The signal generator is set to the desired operating frequency and the output response is measured as a function of the signal generator level.



Figure 3: Source Level Measurement Setup

Once the output response is measured, an accurate measurement of the source voltage from the signal generator is made by measuring the signal generator levels with a power meter as shown in Fig.3. The signal generator levels are those settings which were used for the detector output response measurement.

As long as the detector presents a good match to the generator, or a similar match as the power meter, this technique is applicable. The reflection coefficient magnitude of the Narda detector in combination with the $1\text{k}\Omega$ load was found to be -20dB at 3.9GHz which is the CKM separator cavity frequency.

Measurement Data

The diode detector calibration procedure was applied to the 3 detectors currently used in the CKM SCRF Q-measurement system at the A0 North Cave. Measurements were made at source frequencies of 3.9, 3.92, 3.94, and 3.96 GHz . The experimental output response was then taken as the average of these measurements. The generalized regression method for determining the coefficients to Eq.6 for each detector's response was performed using Mathcad². The coefficients for each detector are shown in Table 1. The detailed processing of the data is documented in Appendix A.

Table 1
CKM Peak Detector Calibration Coefficients

Detector & $1\text{k}\Omega$ Load Serial #	c0	c1	c2
A0-CKM-001	2.24	0.033	1075
A0-CKM-002	2.29	0.029	1299
A0-CKM-003	2.26	0.0298	1281

A typical response curve is depicted in Fig. 4 which represents detector A0-CKM-001.

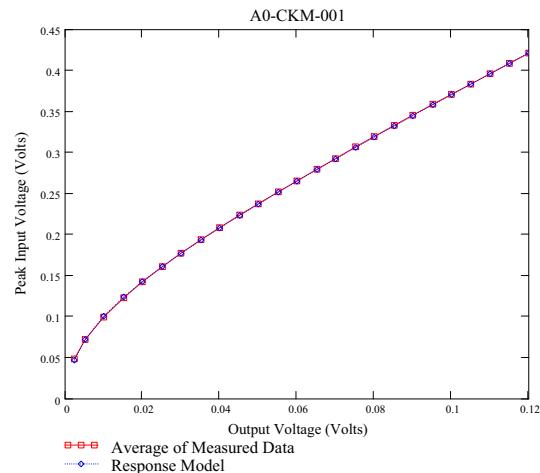


Figure 4: A0-CKM-001 Output Response

² Mathcad is written by Mathsoft, Inc. 101 Main Street, Cambridge, MA 02142

The percent error of the response model equation relative to the experimental data at each of the four source frequencies for each detector can be found in figures 5 through 7. Clearly the response model equation is well within +/-1% of the experimental data down to 20mV of output detector voltage.

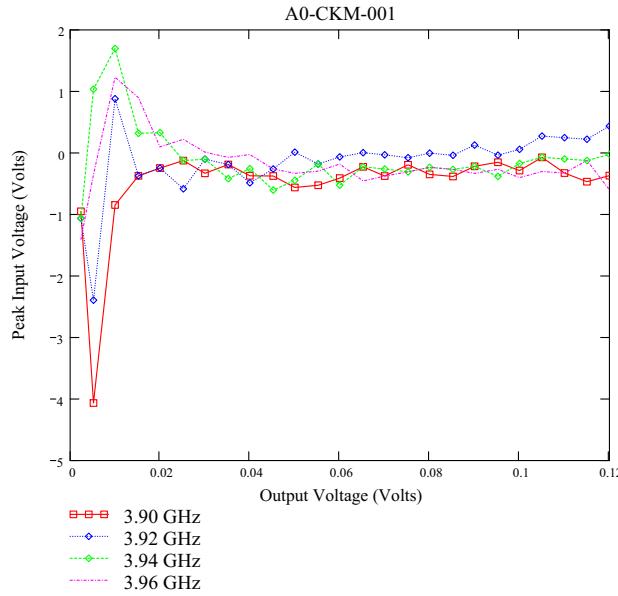


Figure 5: A0-CKM-001 Response Model Error

Dynamic Response

To confirm that decay time measurements are not adversely affected by the dynamic response of the peak detector, the decay time of both the HPE4422B signal generator and the Narda diode with the $1\text{k}\Omega$ load was measured. This decay measurement is shown in Fig. 8. The time constant of the signal generator and detector combination is of the order of 1/10 of a microsecond. The electric field decay time constant of the CKM SCRF 3.9GHz cavity is of the

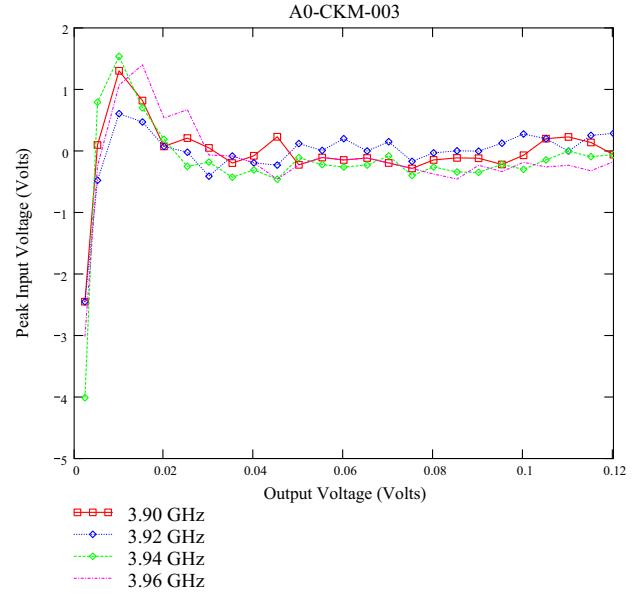


Figure 7: A0-CKM-003 Response Model Error

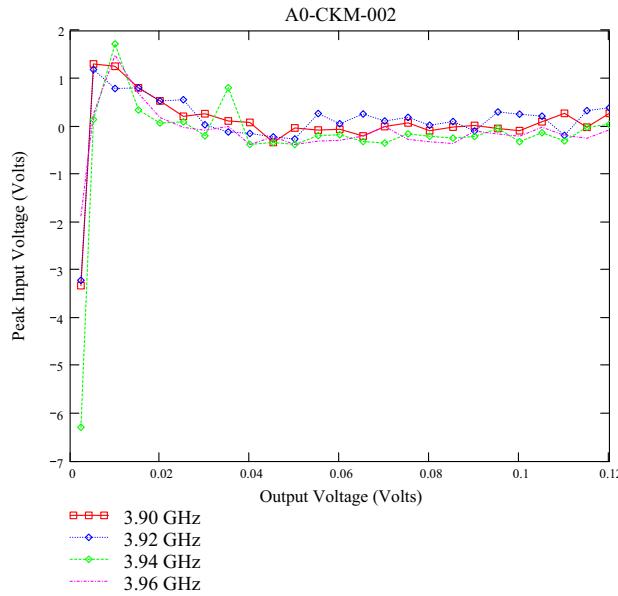


Figure 6: A0-CKM-002 Response Model Error

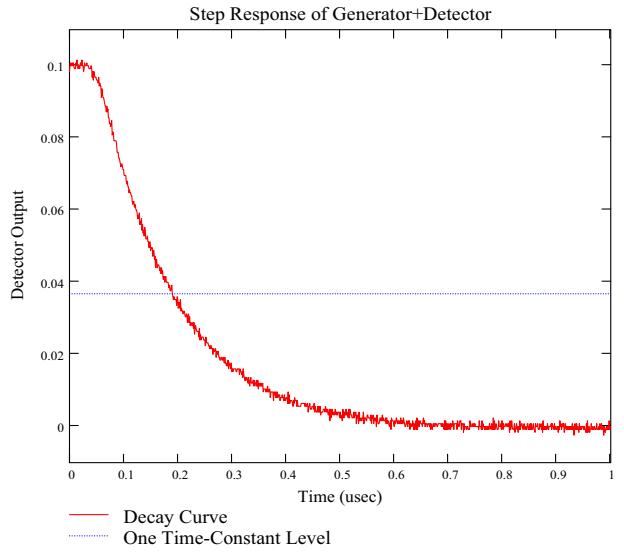


Figure 8: Signal Generator & Detector Decay

order of tens to hundreds of milliseconds with a quality factor on the order of 10^8 to 10^9 . Thus, the signal generator and detector decay time is negligible compared to the cavity decay time.

Conclusion

The response models for the CKM SCRF diode peak detectors were found to be within +/-1% of the measurement data over a practical range. It is suggested that the presented calibration procedure can be used for diode detectors within our RF systems.

Remarks

I would like to thank Rick Zifko for actually measuring all of the experimental data.

Appendix A

Experimental Data

A0-CKM-001 Measurement Data

Tektronix Scope Reading (mV)	3.90 GHz		3.92 GHz		3.94 GHz		3.96 GHz	
	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)
2.4	-16.38	-16.39	-16.38	-16.38	-16.38	-16.38	-16.38	-16.35
5.2	-12.26	-12.27	-12.4	-12.42	-12.74	-12.72	-12.64	-12.6
10	-9.62	-9.61	-9.76	-9.76	-9.84	-9.83	-9.82	-9.79
15.2	-7.84	-7.81	-7.84	-7.81	-7.9	-7.87	-7.96	-7.92
20	-6.62	-6.6	-6.62	-6.6	-6.68	-6.65	-6.68	-6.63
25.2	-5.58	-5.56	-5.54	-5.52	-5.6	-5.56	-5.64	-5.59
30	-4.76	-4.73	-4.78	-4.75	-4.8	-4.75	-4.82	-4.76
35.2	-4.02	-3.98	-4.02	-3.98	-4.02	-3.96	-4.06	-3.99
40	-3.4	-3.34	-3.38	-3.33	-3.4	-3.35	-3.46	-3.37
45.2	-2.78	-2.73	-2.78	-2.74	-2.78	-2.71	-2.82	-2.74
50	-2.22	-2.2	-2.26	-2.25	-2.24	-2.21	-2.26	-2.22
55.2	-1.72	-1.69	-1.74	-1.72	-1.76	-1.72	-1.76	-1.71
60	-1.28	-1.26	-1.32	-1.29	-1.3	-1.25	-1.34	-1.28
65.2	-0.86	-0.83	-0.88	-0.85	-0.88	-0.83	-0.86	-0.81
70	-0.46	-0.43	-0.5	-0.46	-0.5	-0.44	-0.48	-0.43
75.2	-0.1	-0.05	-0.1	-0.06	-0.1	-0.04	-0.1	-0.04
80	0.26	0.31	0.24	0.28	0.24	0.3	0.24	0.3
85.2	0.62	0.67	0.6	0.64	0.6	0.66	0.58	0.66
90	0.92	0.97	0.9	0.94	0.9	0.97	0.9	0.98
95.2	1.24	1.29	1.24	1.28	1.24	1.31	1.22	1.3
100	1.54	1.59	1.5	1.56	1.5	1.58	1.52	1.6
105	1.8	1.86	1.78	1.83	1.78	1.86	1.8	1.88
110	2.1	2.16	2.06	2.11	2.06	2.14	2.06	2.16
115	2.38	2.44	2.32	2.38	2.34	2.41	2.32	2.41
120	2.64	2.69	2.58	2.62	2.58	2.66	2.62	2.71

Mathcad File

Serial # A0-CKM-001

```

data := READPRN("y:\project\hlrf\Berenc_Zifko\A0_Cavity\PeakDetector_Calibration\narda503PD_Serial001.txt")
k := 0 .. rows(data) - 1
freq := 
$$\begin{pmatrix} 3.9 \\ 3.92 \\ 3.94 \\ 3.96 \end{pmatrix} \cdot \text{GHz}$$
 j := 0 .. rows(freq) - 1 input_dBmk,j := datak,3..j+2 inputk,j :=  $\frac{\sqrt{0.001 \cdot 50 \cdot 2} \cdot 10}{20}$ 
input3.90GHz := submatrix(input, 0, rows(input) - 1, 0, 0) input3.92GHz := submatrix(input, 0, rows(input) - 1, 1, 1)
input3.94GHz := submatrix(input, 0, rows(input) - 1, 2, 2) input3.96GHz := submatrix(input, 0, rows(input) - 1, 3, 3)
outputk :=  $\frac{\text{data}_{k,0}}{1000}$ 

```

Before fitting a function to the data, let's create an averaged data array.

$$\begin{aligned}
\text{input}_{\text{avg}_k} &:= \frac{\text{input}_{k,0} + \text{input}_{k,1} + \text{input}_{k,2} + \text{input}_{k,3}}{4} \\
F(v_o, c) &:= \begin{pmatrix} c_0 \cdot v_o + c_1 \cdot \ln(c_2 \cdot v_o + 1) \\ v_o \\ \ln(c_2 \cdot v_o + 1) \\ \frac{c_1 \cdot v_o}{c_2 \cdot v_o + 1} \end{pmatrix} \quad c_{\text{guess}} := \begin{pmatrix} 1 \\ 5 \\ 1 \end{pmatrix} \quad P := \text{genfit}(\text{output}, \text{input}_{\text{avg}}, c_{\text{guess}}, F) \\
&\qquad\qquad\qquad \text{Solution} \qquad\qquad\qquad \text{Truncated} \\
P &= \begin{pmatrix} 2.241 \\ 0.0331 \\ 1.0752 \times 10^3 \end{pmatrix} \quad P := \begin{pmatrix} 2.24 \\ 0.033 \\ 1075 \end{pmatrix}
\end{aligned}$$

$$\text{input_fit}(v_o) := F(v_o, P)_0$$

Error between response model and actual data:

$$\begin{aligned}
\% \text{Error_func_fit}_{3.9_k} &:= \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.90GHz_k}}{\text{input}_{3.90GHz_k}} \cdot 100 \quad \% \text{Error_func_fit}_{3.92_k} := \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.92GHz_k}}{\text{input}_{3.92GHz_k}} \cdot 100 \\
\% \text{Error_func_fit}_{3.94_k} &:= \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.94GHz_k}}{\text{input}_{3.94GHz_k}} \cdot 100 \quad \% \text{Error_func_fit}_{3.96_k} := \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.96GHz_k}}{\text{input}_{3.96GHz_k}} \cdot 100
\end{aligned}$$

A0-CKM-002 Measurement Data

Tektronix Scope Reading (mV)	3.90 GHz		3.92 GHz		3.94 GHz		3.96 GHz	
	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)
2.4	-16.3	-16.35	-16.32	-16.36	-16.4	-16.08	-16.46	-16.48
5.2	-13.2	-13.05	-13.02	-13.04	-12.92	-12.95	-12.96	-12.96
10	-10.12	-10.16	-10.08	-10.12	-10.18	-10.2	-10.18	-10.18
15.2	-8.28	-8.29	-8.28	-8.29	-8.26	-8.25	-8.3	-8.28
20	-7.02	-7.04	-7.02	-7.04	-7	-7	-7.02	-7.01
25.2	-5.94	-5.95	-5.96	-5.98	-5.94	-5.94	-5.94	-5.93
30	-5.12	-5.13	-5.1	-5.11	-5.1	-5.09	-5.12	-5.1
35.2	-4.34	-4.34	-4.32	-4.32	-4.32	-4.4	-4.36	-4.33
40	-3.72	-3.7	-3.68	-3.68	-3.68	-3.66	-3.7	-3.66
45.2	-3.06	-3.04	-3.06	-3.05	-3.06	-3.04	-3.1	-3.05
50	-2.56	-2.54	-2.54	-2.52	-2.54	-2.51	-2.56	-2.51
55.2	-2	-2.01	-2.04	-2.04	-2.02	-2	-2	-1.99
60	-1.56	-1.56	-1.56	-1.57	-1.58	-1.55	-1.56	-1.54
65.2	-1.1	-1.09	-1.12	-1.13	-1.1	-1.08	-1.12	-1.09
70	-0.72	-0.71	-0.72	-0.72	-0.7	-0.68	-0.74	-0.71
75.2	-0.32	-0.31	-0.32	-0.32	-0.32	-0.29	-0.32	-0.28
80	0.04	0.06	0.04	0.05	0.04	0.07	0.04	0.08
85.2	0.4	0.42	0.4	0.41	0.4	0.44	0.4	0.45
90	0.7	0.74	0.72	0.75	0.7	0.76	0.7	0.75
95.2	1.04	1.08	1.02	1.05	1.02	1.08	1.04	1.09
100	1.34	1.38	1.32	1.35	1.34	1.4	1.32	1.39
105	1.62	1.66	1.62	1.65	1.62	1.68	1.6	1.67
110	1.88	1.93	1.92	1.97	1.9	1.98	1.9	1.97
115	2.18	2.23	2.16	2.2	2.16	2.23	2.18	2.25
120	2.42	2.47	2.42	2.46	2.42	2.49	2.42	2.5

Mathcad File

Serial # A0-CKM-002

```

data := READPRN("y:\project\hlrf\Berenc_Zifko\A0_Cavity\PeakDetector_Calibration\narda503PD_Serial002.txt")
k := 0 .. rows(data) - 1
freq := 
$$\begin{pmatrix} 3.9 \\ 3.92 \\ 3.94 \\ 3.96 \end{pmatrix} \cdot \text{GHz}$$
 j := 0 .. rows(freq) - 1 input_dBmk,j := datak,3..j+2 inputk,j :=  $\frac{\sqrt{0.001 \cdot 50 \cdot 2} \cdot 10}{20}$ 
input3.90GHz := submatrix(input, 0, rows(input) - 1, 0, 0) input3.92GHz := submatrix(input, 0, rows(input) - 1, 1, 1)
input3.94GHz := submatrix(input, 0, rows(input) - 1, 2, 2) input3.96GHz := submatrix(input, 0, rows(input) - 1, 3, 3)
outputk :=  $\frac{\text{data}_{k,0}}{1000}$ 

```

Before fitting a function to the data, let's create an averaged data array.

$$\begin{aligned}
\text{input}_{\text{avg}_k} &:= \frac{\text{input}_{k,0} + \text{input}_{k,1} + \text{input}_{k,2} + \text{input}_{k,3}}{4} \\
F(v_o, c) &:= \begin{pmatrix} c_0 \cdot v_o + c_1 \cdot \ln(c_2 \cdot v_o + 1) \\ v_o \\ \ln(c_2 \cdot v_o + 1) \\ \frac{c_1 \cdot v_o}{c_2 \cdot v_o + 1} \end{pmatrix} \quad c_{\text{guess}} := \begin{pmatrix} 5 \\ 1 \\ 1 \end{pmatrix} \\
P &:= \text{genfit}(\text{output}, \text{input}_{\text{avg}}, c_{\text{guess}}, F) \\
&\qquad\qquad\qquad \text{Solution} \qquad\qquad\qquad \text{Truncated} \\
P &= \begin{pmatrix} 2.2929 \\ 0.029 \\ 1.2989 \times 10^3 \end{pmatrix} \quad P := \begin{pmatrix} 2.29 \\ 0.029 \\ 1299 \end{pmatrix}
\end{aligned}$$

$$\text{input_fit}(v_o) := F(v_o, P)_0$$

Error between response model and actual data:

$$\begin{aligned}
\% \text{Error_func_fit}_{3.9_k} &:= \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.90GHz_k}}{\text{input}_{3.90GHz_k}} \cdot 100 \quad \% \text{Error_func_fit}_{3.92_k} := \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.92GHz_k}}{\text{input}_{3.92GHz_k}} \cdot 100 \\
\% \text{Error_func_fit}_{3.94_k} &:= \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.94GHz_k}}{\text{input}_{3.94GHz_k}} \cdot 100 \quad \% \text{Error_func_fit}_{3.96_k} := \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.96GHz_k}}{\text{input}_{3.96GHz_k}} \cdot 100
\end{aligned}$$

A0-CKM-003 Measurement Data

Tektronix Scope Reading (mV)	3.90 GHz		3.92 GHz		3.94 GHz		3.96 GHz	
	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)	Signal Generator Power Level (dBm)	Power Meter Reading (dBm)
2.4	-16.24	-16.29	-16.24	-16.29	-16.12	-16.15	-16.22	-16.24
5.2	-12.76	-12.81	-12.72	-12.76	-12.84	-12.87	-12.78	-12.78
10	-10	-10.04	-9.94	-9.98	-10.02	-10.06	-10	-10.02
15.2	-8.14	-8.18	-8.12	-8.15	-8.16	-8.17	-8.24	-8.23
20	-6.88	-6.9	-6.88	-6.9	-6.88	-6.91	-6.94	-6.94
25.2	-5.84	-5.86	-5.82	-5.84	-5.82	-5.82	-5.9	-5.9
30	-5.02	-5.03	-4.98	-4.99	-5	-5.01	-5.04	-5.02
35.2	-4.24	-4.24	-4.24	-4.25	-4.22	-4.22	-4.28	-4.25
40	-3.62	-3.62	-3.6	-3.61	-3.62	-3.6	-3.64	-3.61
45.2	-3.04	-3.03	-3	-2.99	-2.98	-2.97	-3	-2.97
50	-2.44	-2.47	-2.48	-2.5	-2.48	-2.48	-2.48	-2.47
55.2	-1.94	-1.96	-1.94	-1.97	-1.94	-1.95	-1.96	-1.96
60	-1.5	-1.51	-1.52	-1.54	-1.5	-1.5	-1.52	-1.51
65.2	-1.06	-1.06	-1.06	-1.07	-1.06	-1.05	-1.08	-1.06
70	-0.66	-0.66	-0.68	-0.69	-0.68	-0.67	-0.68	-0.66
75.2	-0.26	-0.25	-0.26	-0.26	-0.26	-0.24	-0.28	-0.25
80	0.08	0.09	0.08	0.08	0.08	0.1	0.08	0.11
85.2	0.44	0.45	0.44	0.44	0.44	0.47	0.44	0.48
90	0.76	0.77	0.74	0.76	0.74	0.79	0.74	0.78
95.2	1.08	1.11	1.06	1.08	1.06	1.11	1.08	1.12
100	1.36	1.39	1.34	1.36	1.36	1.41	1.34	1.4
105	1.64	1.66	1.64	1.66	1.64	1.69	1.64	1.7
110	1.92	1.94	1.92	1.96	1.9	1.96	1.92	1.98
115	2.18	2.22	2.18	2.21	2.18	2.24	2.2	2.26
120	2.46	2.5	2.44	2.47	2.44	2.5	2.44	2.51

Mathcad File

Serial # A0-CKM-003

```

data := READPRN("y:\project\hlrf\Berenc_Zifko\A0_Cavity\PeakDetector_Calibration\narda503PD_Serial003.txt")
k := 0 .. rows(data) - 1
freq := 
$$\begin{pmatrix} 3.9 \\ 3.92 \\ 3.94 \\ 3.96 \end{pmatrix} \cdot \text{GHz}$$
 j := 0 .. rows(freq) - 1 input_dBmk,j := datak,3..j+2 inputk,j :=  $\frac{\sqrt{0.001 \cdot 50 \cdot 2} \cdot 10}{20}$ 
input3.90GHz := submatrix(input, 0, rows(input) - 1, 0, 0) input3.92GHz := submatrix(input, 0, rows(input) - 1, 1, 1)
input3.94GHz := submatrix(input, 0, rows(input) - 1, 2, 2) input3.96GHz := submatrix(input, 0, rows(input) - 1, 3, 3)
outputk :=  $\frac{\text{data}_{k,0}}{1000}$ 

```

Before fitting a function to the data, let's create an averaged data array.

$$\begin{aligned}
\text{input}_{\text{avg}_k} &:= \frac{\text{input}_{k,0} + \text{input}_{k,1} + \text{input}_{k,2} + \text{input}_{k,3}}{4} \\
F(v_o, c) &:= \begin{pmatrix} c_0 \cdot v_o + c_1 \cdot \ln(c_2 \cdot v_o + 1) \\ v_o \\ \ln(c_2 \cdot v_o + 1) \\ \frac{c_1 \cdot v_o}{c_2 \cdot v_o + 1} \end{pmatrix} \quad c_{\text{guess}} := \begin{pmatrix} 1 \\ 5 \\ 1 \end{pmatrix} \quad P := \text{genfit}(\text{output}, \text{input}_{\text{avg}}, c_{\text{guess}}, F) \\
&\qquad\qquad\qquad \text{Solution} \qquad\qquad\qquad \text{Truncated} \\
P &= \begin{pmatrix} 2.2638 \\ 0.0298 \\ 1.2807 \times 10^3 \end{pmatrix} \quad P := \begin{pmatrix} 2.26 \\ 0.0298 \\ 1281 \end{pmatrix}
\end{aligned}$$

$$\text{input_fit}(v_o) := F(v_o, P)_0$$

Error between response model and actual data:

$$\begin{aligned}
\% \text{Error_func_fit}_{3.9_k} &:= \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.90GHz_k}}{\text{input}_{3.90GHz_k}} \cdot 100 \quad \% \text{Error_func_fit}_{3.92_k} := \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.92GHz_k}}{\text{input}_{3.92GHz_k}} \cdot 100 \\
\% \text{Error_func_fit}_{3.94_k} &:= \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.94GHz_k}}{\text{input}_{3.94GHz_k}} \cdot 100 \quad \% \text{Error_func_fit}_{3.96_k} := \frac{\text{input_fit}(\text{output}_k) - \text{input}_{3.96GHz_k}}{\text{input}_{3.96GHz_k}} \cdot 100
\end{aligned}$$